SAFE ACCEPTABLE STANDOFF DISTANCES FOR BODY WEARABLE ANTENNAS

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ABSTRACT

Soldier Manpack radios for programs such as Future Warrior Technology Integration (FWTI), Land Warrior (LW), and JTRS Handheld Manpack and Small Form Fit (HMS) use standard whip antennas which can be as large as a meter in height. During combat operations, the whip antenna can become entangled, damaged or destroyed, causing a degradation or loss of communications. In addition to the antenna's size, whip antennas present electrical challenges in that they are vertically polarized and narrowband. When Soldiers are kneeling or prone to the ground, the efficiency strength of communications between nodes may be reduced due to the polarization mismatch between antennas. Finally, the narrowband design of the whip antenna cannot support the newer generation of wideband waveforms. Body Wearable Antennas (BWA) can mitigate these deficiencies and increase the Soldiers' communication capabilities.

Recent concerns about the RF Radiation Hazards of BWA have arisen in both the commercial and military communities. Since a BWA is in close proximity to the Soldier's body, there is a concern that the RF exposure creates a potentially unsafe "Electromagnetic Hotspot." The US Army Center for Health Promotion and Preventative Medicine (CHPPM) requires a fully certified RF Safety Assessment of BWAs before they are worn by Soldiers. The Department of Defense uses DoDl 6055.11 and IEEE C95.1-1992/1999 "Standard for Safety Levels with Respect to Human Exposure to RF Electromagnetic Fields, 3 kHz to 300 GHz" as the basis for the assessment. Within these standards, the levels of these RF exposures are quantified using the Specific Absorption Rate (SAR), which is a measure of the rate at which radio frequency is absorbed by the body when exposed to radio-frequency electromagnetic field. In this paper, acceptable stand-off distances between the BWA and the Soldier's body are identified using the SAR parameter as a metric to measure RF exposure to human tissue. Using the Finite Difference Time Domain (FDTD) Computational Electromagnetics Phantom Shell model, the SAR of a BWA, developed by the MegaWave Corporation under a US Army CERDEC contract, is evaluated for various standoff distances. The findings of the analysis indicate that if a 1g SAR specification is adopted, the MegaWave BWA requires a standoff distance of 46 mm.

If a 10g SAR specification is adopted, a standoff distance of at least 31 mm is required.

1. INTRODUCTION

Over the past four years, the CERDEC Space and Terrestrial Communications Directorate, Antenna Technology and Analysis (ATA) Branch, initiated a number of Broad Agency Announcements (BAA) and Small Business Innovative Research (SBIR) projects to develop BWAs. Under these projects, the ATA Branch developed fourteen different designs of BWAs to support programs such as FWTI, LW, and PM HMS. In the past, the ATA Branch worked with the Naval Health Center – Detachment in at Brooks City Base, San Antonio, TX to perform safety assessments of BWA using the temperature rise method. However, due to the great number of BWAs being developed, it became imperative for the ATA Branch to build its own Specific Absorption Rate (SAR) Laboratory. Working with Dr. Michael Manning from IndexSAR, CERDEC acquired a full working SAR Measurement Laboratory with a Phantom Shell and the Specific Anthropomorphic Mannequin (SAM) Phantom. In this paper, using Modeling and Simulation, standoff placements of the MegaWave Cluster 5 High Band Dipole BWA are presented.

2. PROPOSED APPROACH

The MegaWave Corporation, under a CERDEC BAA, developed the BWA shown in Fig 1. This antenna is a Wideband Directional Dipole that operates between 1350 – 2700 MHz. The antenna elements were designed to be integrated onto the FWTI Ensemble's left front and right rear shoulder straps.

Fig. 1 Cluster 5 High Band BWA System

Report Documentation Page

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 DEC 2008	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Safe Acceptable Standoff Distances For Body Wearable Antennas	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
U.S. Anny Communications-Electronics Research, Development & Engineering Center Building 2700, Myer Center Fort Monmouth, NJ 07703	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002187. Proceedings of the Army Science Conference (26th) Held in Orlando, Florida on 1-4 December 2008, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

Safety Assessments of the Megawave BWA were modeled at 1450, 1800, 1900, 1950, 2000, and 2450 MHz, using the IEEE 1528 [2] & IEC 62209 standards and the appropriate Phantom Box models. The Phantom Box models simulate human tissue at these frequencies.

2.1 Finite Difference Time Domain (FDTD)

The Finite Difference Time Domain (FDTD) technique [1] was used to create the Phantom Models, appropriate liquids that simulate human tissue, validation dipoles, and MGW High Band Cluster 5 BWA. FDTD is based on Maxwell's curl equations.

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu} \nabla \times E - \frac{\rho'}{\mu} H \qquad (1)$$

$$\frac{\partial E}{\partial t} = -\frac{1}{\varepsilon} \nabla \times H - \frac{\sigma}{\varepsilon} E \qquad (2)$$

Yee's Algorithm is used to calculate Maxwell's curl equations based on finite difference approximations of space derivatives and time derivatives. Two key parameters that are important for accuracy and stability when using the FDTD technique are the cell size (α) and the time step (Δt) [1].

$$\alpha \leq \frac{\lambda}{10} \qquad (3)$$

$$\Delta t \leq \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \qquad (4)$$

A Specific Absorption Rate (SAR) Figure of Merit (FoM) which is related to the E-field generated by the BWA, is calculated to both a 1 gram and 10 gram average

$$SAR = \frac{\sigma |E|^2}{\rho} \qquad (5)$$

The conductivity of the tissue is given by σ (S/m), the mass density of the tissue is given by ρ (kg/m^3) and the rms electric field strength is given by E (V/m). The maximum cell size must be less than or equal to $1/10^{th}$ (some cases $1/20^{th}$) the wavelength of the highest operational frequency. In this paper, an FDTD model of the validation dipole is shown in Fig 2.

Fig. 2 FDTD Validation Dipole.

2.2 FDTD Phantom Shells and Liquids

The box phantom is a simple container which, in the context of compliance testing, is used only for system performance checking and validation. It presents a flat bottom to the reference source so that errors due to variations in separation from the source are minimized. It should be filled with the same liquid as is used in an actual test, formulated for the appropriate frequency. Shown in Fig 3 is an FDTD model of the box phantom used for 1450 MHz.
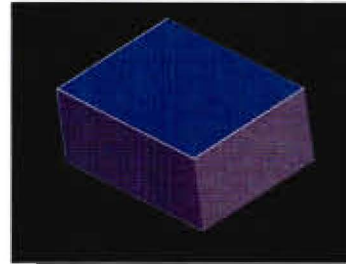

Fig. 3 FDTD 1450MHz Box Phantom.

The standards give certain minimum dimensional and material requirements. The minimum transverse dimensions (width and length) should be such that the SAR measurements are not affected by more than 1.0%. Table 1 illustrates the dimensions used for the box phantoms.

Frequency (MHz)	Phantom Dimensions (mm) (x,y,z)
1450	240, 160, 150
1800	220, 160, 150
1900	220, 160, 150
1950	220, 160, 150
2000	160, 140, 150
2450	180, 120, 150

Table 1 Phantom Dimensions

The box phantom shell thickness is 2.0mm and the box phantom permittivity is 3.7. The liquid properties used for the selected test frequencies are shown in Table 2.

Frequency (MHz)	Permittivity (ε'_r)	Conductivity (σ)
1450	40.5	1.20
1800	40.0	1.40
1900	40.0	1.40
1950	40.0	1.40
2000	39.8	1.49
2450	39.2	1.80

Table 2 Liquid Permittivity and Conductivity value

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2.3 FDTD Dipole Antenna Geometry

The standards have published values for dipoles at various frequencies. The dipole, shown in Fig 4 is treated as a reference dipole with a known SAR value for 1g and 10g. Based on the standards, the dipole is placed 10mm beneath the box phantom for the selected test frequencies. The dipole is used to validate the entire systems including the correct liquid permittivity and conductivity, and the correct phantom shell. In the model, 1 watt input power is fed.
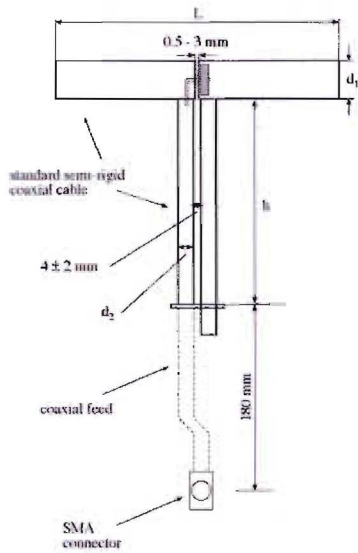

Fig. 4 Dipole Antenna Design

Six different dipole antennas were used for the six test frequencies. Table 3 shows the different lengths of the dipoles. The dipoles are 3.6 mm in diameter.

Frequency (MHz)	Length (mm)
1450	89.1
1800	72.0
1900	68.0
1950	66.3
2000	64.5
2450	51.5

Table 3 Dipole Antenna lengths

2.4 FDTD Dipole Validation

Standards have required SAR values for dipole tests for 1g and 10g. A dipole validation test for an experimental setup ensures all equipment is working properly, the correct power is delivered, and the liquid used has the correct dielectric properties. For the model, the dipole validation ensures that the liquid used has the correct dielectric properties. Using FDTD, six dipole models were created using a 2 x 2 x 2 mm

grid spacing. Since the MegaWave BWA model used grid dimensions of 0.381 x 0.9525 x 1.27 mm, a sub-grid spacing's using these dimensions were also incorporated. The dimensions were precisely maintained so that the geometry and performance of the MegaWave BWA was not altered. In addition, four box phantoms and four different tissue-simulating liquids were created. The 1800 MHz box phantom along with the 1800 MHz dipole is shown in Fig 5.
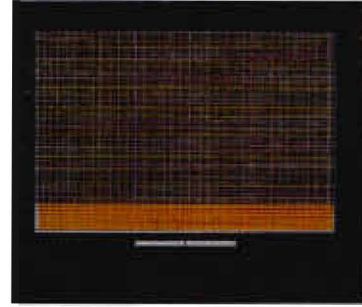

Fig. 5 1800MHz Box Phantom with 1800MHz Dipole

In accordance with the published standards, the dipole's SAR must be within 5% error of the published results. Simulations to validate the box phantoms used were run at 1450, 1800, 1900, 1950, 2000, and 2450MHz. Tables 4 and 5 provide the results for the dipole models.

Frequency (MHz)	Standard SAR (1g)	Modeled SAR (1g)	Error %
1450	29W/kg	28.186W/kg	2.81%
1800	38.1W/kg	37.395W/kg	1.85%
1900	39.7W/kg	39.722W/kg	0.06%
1950	40.5W/kg	39.061W/kg	3.55%
2000	41.1W/kg	39.773W/kg	3.23%
2450	52.4W/kg	50.864W/kg	2.93%

Table 4 1g SAR Dipole Validation Results

Frequency (MHz)	Standard SAR (10g)	Modeled SAR (1g)	Error %
1450	16W/kg	15.807W/kg	1.21%
1800	19.8W/kg	19.705W/kg	0.48%
1900	20.5W/kg	20.728W/kg	1.10%
1950	20.9W/kg	20.41W/kg	2.34%
2000	21.1W/kg	20.731W/kg	1.75%
2450	24W/kg	23.892W/kg	0.45%

Table 5 10g SAR Dipole Validation Result

Tables 4 and 5 indicate that that the simulation results are within 5% error and validate the box phantom models. The 2D SAR Hot Spots at 1450 MHz and 1800 MHz are shown in Fig 6.
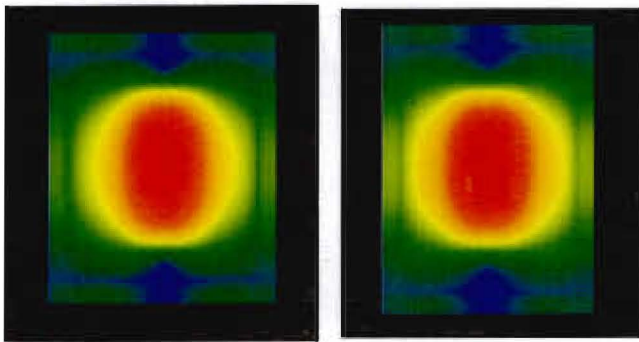
3

Fig. 6 1450MHz and 1800MHz 2D SAR Hot Spot for Dipoles

2.5 FDTD MegaWave BWA Model

The Mega Wave High Band BWA operates within 1350 – 2700 MHz. The geometry is a directional dipole antenna with two elements connecting to a Wilkinson power divider. The mounting location of one of the antenna elements is shown in Figure 7. The second antenna element is positioned on the Soldier's left rear shoulder.

Fig 7 MegaWave BWA Mounting Location

The two antenna elements are connected to a power splitter. The measured gain of the antenna from 1350 – 2700 MHz is shown in Figure 8. The gain of the antenna was measured using a mannequin filled with a saline water solution.
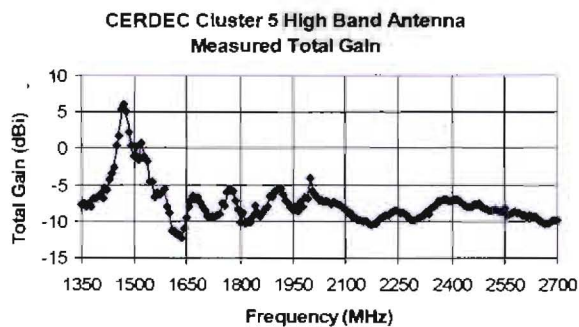
Fig 8 MegaWave BWA Gain

MegaWave provided the FDTD model to perform the SAR simulations in FDTD. The MegaWave BWA model used for the SAR simulations is provided in Figure 9.

Fig 9 MegaWave BWA FDTD Model

To avoid changing the dimensions of the MegaWave BWA Model, a sub-grid was used within the 2 mm by 2 mm by 2 mm grid. The sub-grid was 0.381 mm by 0.9525 mm by 1.27 mm. The MegaWave BWA in the mesh mode is shown in Figure 10.
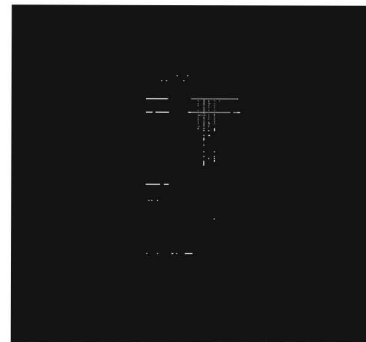

Fig 10 MegaWave BWA FDTD Model in Mesh Mode

To verify that both the MegaWave Model and the sub-gridded model agree, the sub-gridded model was run with the same test frequencies. Elevation patterns of the sub gridded model, validated against the MegaWave Model, are shown if Figure 11. The two patterns show very good agreement.
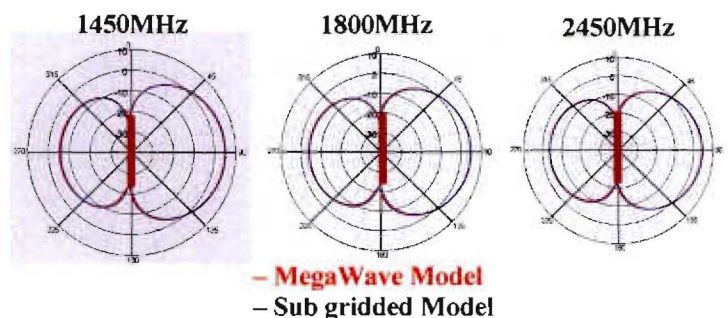

Fig 11 MegaWave BWA Validation against Sub Gridded Model

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3. MEGAWAVE BWA SAR SIMULATION AND ANALYSIS

The MegaWave BWA was placed underneath the box phantoms created for the dipole validations. The feed of the MegaWave BWA was treated as the center of the antenna for the SAR simulations since the feed is where the hot spot is usually located. The back of the antenna was positioned on the bottom surface of the box phantom. Initially, the MegaWave BWA was placed on the bottom of the box phantom and moved away from the bottom in increments of 5mm. The 1g and 10g SAR values were computed at every 5mm up to 50mm. The allowable SAR according the standards is 1.6W/kg for 1g and 2.0W/kg for 10g. The following standoff distances were used: 0, 5.334, 9.906, 15.24, 19.812, 25.146, 29.718, 35.052, 40.386, 44.958, and 50.292mm. The SAR simulations were run at 1450, 1800, 1900, 1950, 2000, and 2450MHz.

3.1 1450MHz Simulation Run

Using FDTD, the simulation was run for various standoff distances at a frequency of 1450 MHz. Using the SAR metric, the standoff distance required for safe operation was determined for the MegaWave BWA. This FDTD MegaWave box phantom model is shown in Fig 12.
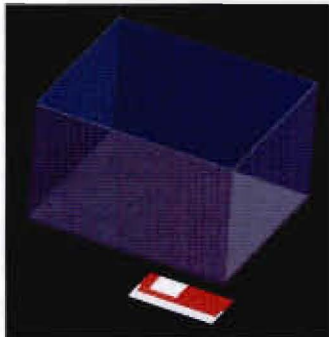

Fig 12 MegaWave BWA Box Phantom Model at 1450MHz

Using FDTD, the simulation was run for various standoff distances at a frequency of 1450 MHz. Using the SAR metric, the standoff distance required for safe operation was determined for the MegaWave BWA. This FDTD MegaWave box phantom model is shown in Fig 13 the 1g SAR average hot spot when the MegaWave BWA is near the box phantom for various standoff distances at 1450 MHz. As expected, the hot spot was most intense at 0 mm separation distance At a standoff distance of 46 mm, the 1g SAR was 1.5961W/kg, which is below the 1.6W/kg specification. Figure 14 shows the 10g SAR average hot spots. At a 36.6 mm standoff distance, the 10g SAR was 1.9932W/kg, which is also below

the 2.0 W/kg specifications. If the 1g SAR specification is adopted, then placing the BWA at or below 46.01mm is considered safe. If the 10g SAR specification is adopted, then placing the BWA at or below 36.575mm is considered safe.
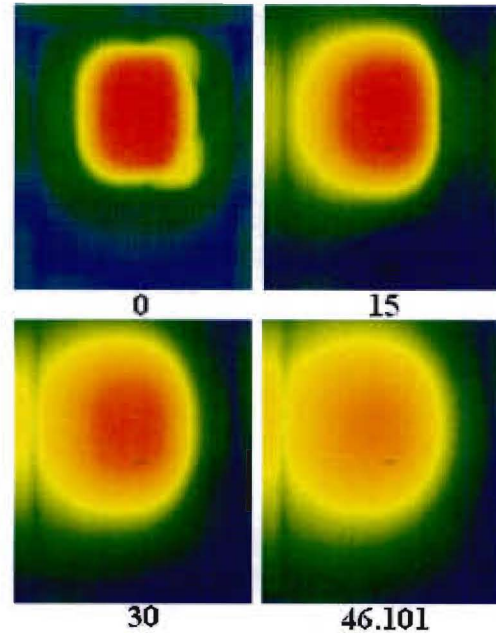

| 0 | 15 |
| 30 | 46.101 |

Fig 13 1450MHZ SAR for 1g Average Hot Spot for various Standoff Distances
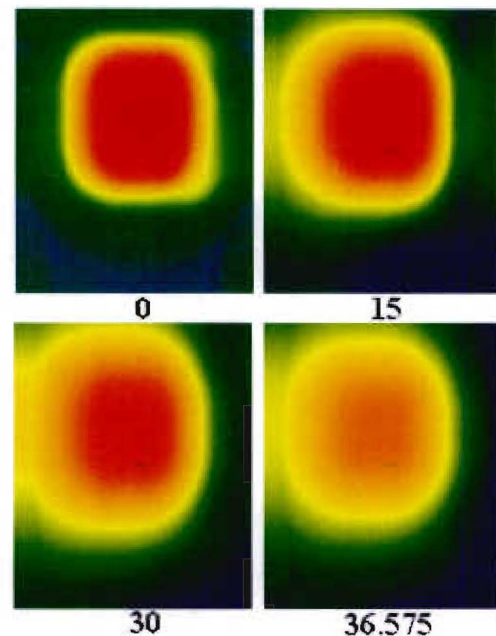

| 0 | 15 |
| 30 | 36.575 |

Fig 14 1450MHZ SAR for and 10g Average Hot Spot for various Standoff Distances

Figure 15 shows the 1g and 10g SARs with respect to the standoff distance at 1450 MHz. As the standoff distance between the box phantom and the MegaWave BWA increases, the SAR decreases. For 1g SAR, at 46mm below the box phantom, a value of 1.6W/kg is reached. For 10g SAR, at 37mm, a value of 2.0W/kg is reached.
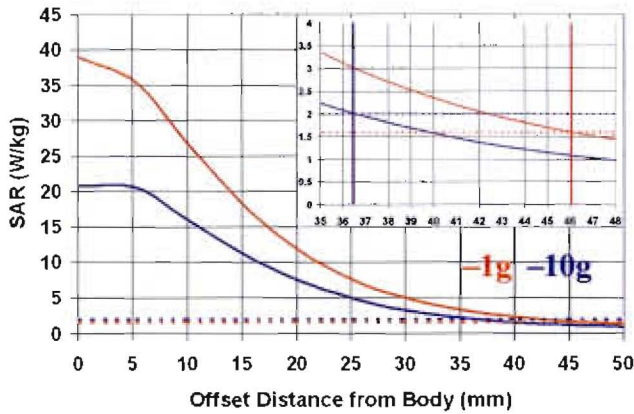

Fig. 15 SAR 1g and 10g against Offset Distance from Body (Box Phantom) for 1450MHz

3.2 1800MHz Simulation Run

Using FDTD, the simulation was run for various standoff distances at a frequency of 1800 MHz. Using the SAR metric, the standoff distance required for safe operation was determined for the MegaWave BWA. The FDTD MegaWave box phantom model at 1800 MHz is shown in Fig 16.
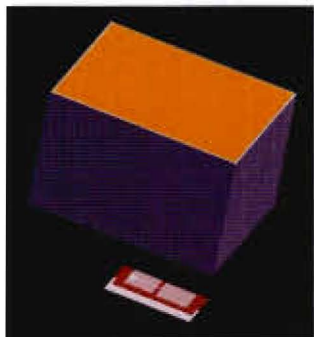

Fig 16 MegaWave BWA Box Phantom Model at 1800MHz

Figure 17 shows the 1g SAR average hot spot when the MegaWave BWA is near the box phantom for various standoff distances at 1800 MHz. As expected, the hot spot was most intense at 0 mm separation distance At 43.1 mm below the box phantom, the 1g SAR was 1.5985W/kg, which is below the 1.6W/kg specification. Figure 18 shows the 10g SAR average hot spots. At 32.8 mm below the box phantom, the 1g SAR was 1.9621W/kg, which is also below the 2. Using

FDTD, the simulation was run for various standoff distances at a frequency of 1800 MHz. Using the SAR metric, the standoff distance required for safe operation was determined for the MegaWave BWA. The FDTD MegaWave box phantom model at 1800 MHz is shown in Fig 16. If the 1g SAR specification is adopted, then placing the BWA at or below 43.1 mm is considered safe. If the 10g SAR specification is adopted, then placing the BWA at or below 32.8 mm is considered safe.
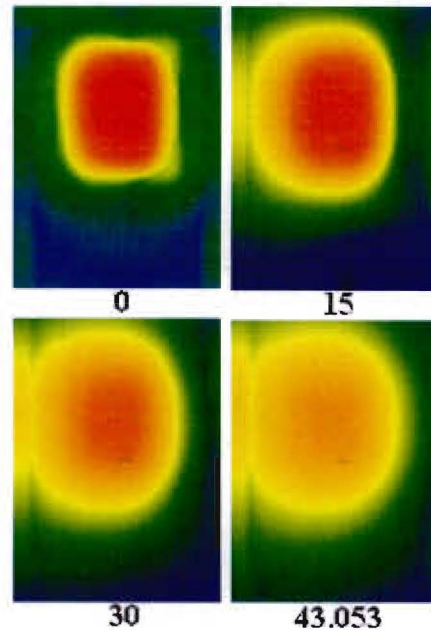

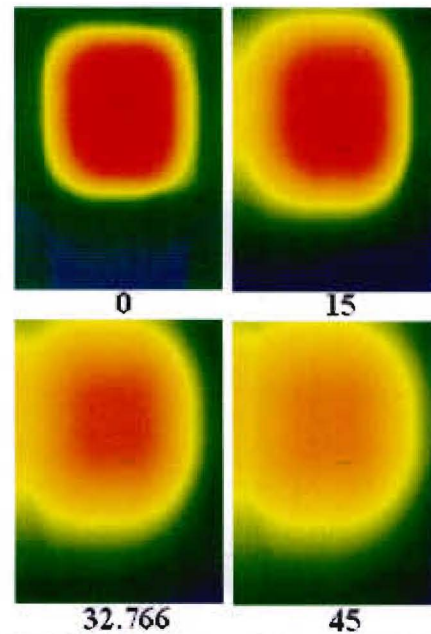Fig 17 1800MHZ SAR for 1g Average Hot Spot for various Standoff Distances

Fig 18 1800MHZ SAR for and 10g Average Hot Spot for various Standoff Distances

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Figure 19 shows the 1g and 10g SARs as a function of standoff distance at a frequency Figure 18 shows the 1g SAR average hot spot when the MegaWave BWA is near the box phantom for various standoff distances at 1800 MHz. As expected, the hot spot was most intense at 0 mm separation distance At 43.1 mm below the box phantom, the 1g SAR was 1.5985W/kg, which is below the 1.6W/kg specification. Figure 19 shows the 10g SAR average hot spots. At 32.8 mm below the box phantom, the 1g SAR was 1.9621W/kg, which is also below the 2. Using FDTD, the simulation was run for various standoff distances at a frequency of 1800 MHz. Using the SAR metric, the standoff distance required for safe operation was determined for the MegaWave BWA. The FDTD MegaWave box phantom model at 1800 MHz is shown in Fig 17. If the 1g SAR specification is adopted, then placing the BWA at or below 43.1 mm is considered safe. If the 10g SAR specification is adopted, then placing the BWA at or below 32.8 mm is considered safe. As the standoff distance between the box phantom and the MegaWave BWA increases, the SAR decreases. For 1g SAR, at 43mm below the box phantom, a value of 1.6W/kg is reached. For 10g SAR, at 33mm, a value of 2.0W/kg is reached.

Fig 20 MegaWave BWA Box Phantom Model at 2450MHz

Shown in Fig 21 is the 1g SAR Average Hot Spot when the MegaWave BWA is near the box phantom for various standoff distances at 2450MHz. The Hot Spot is most intense at 0mm since it is near the box phantom. At around 46.482mm below the box phantom, the SAR for 1g is 1.5976W/kg, which is below the Specification of 1.6W/kg. Shown in Fig 22 are the 10g SAR Average Hot Spots. At around 27.051mm below the box phantom, the SAR for 1g is 1.9697W/kg, which is below the Specification of 2.0W/kg. If the 1g SAR is adopted, then placing the BWA at or below 46.482mm is considered safe. If the 10g SAR is adopted, then placing the BWA at or below 27.051mm is considered safe.
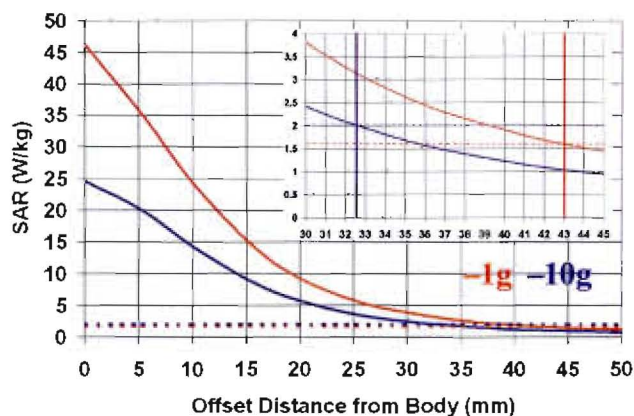

Fig. 19 SAR 1g and 10g against Offset Distance from Body (Box Phantom) for 1800MHz

3.6 2450MHz Simulation Run

Using FDTD, the 2450MHz simulation was run for various standoff distances. Using the SAR, it is determined what the safe standoff distance is for the MegaWave BWA at 2450MHz. This FDTD MegaWave box phantom model is shown in Fig 20.
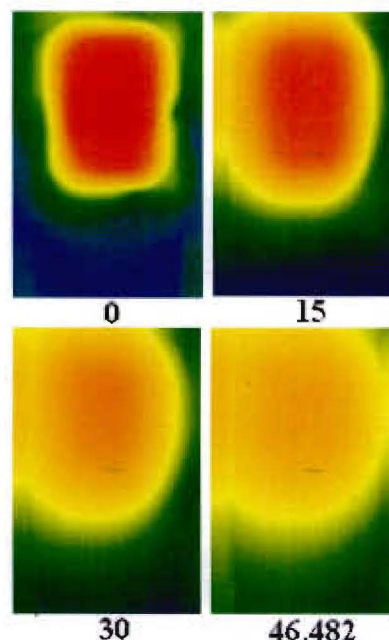

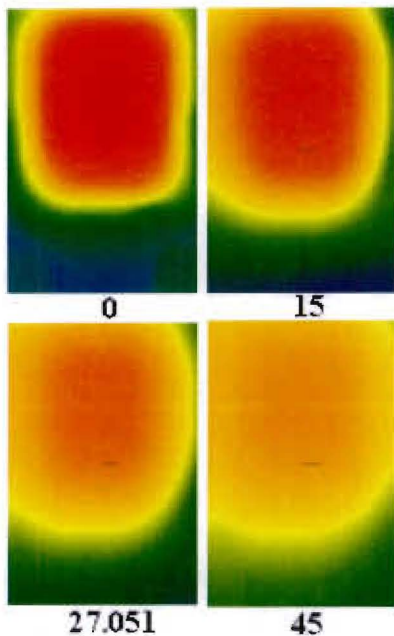Fig 21 2450MHZ SAR for 1g Average Hot Spot for various Standoff Distances

Fig 22 2450MHZ SAR for and 10g Average Hot Spot for various Standoff Distances

Shown in Fig 23 is the SAR 1g and 10g with respect to the standoff distance at 2450MHz. As the standoff distance between the box phantom and the MegaWave BWA increases, the SAR decreases. For 1g SAR, at 46mm below the box phantom, a value of 1.6W/kg is reached. For 10g SAR, at 27mm, a value of 2.0W/kg is reached.
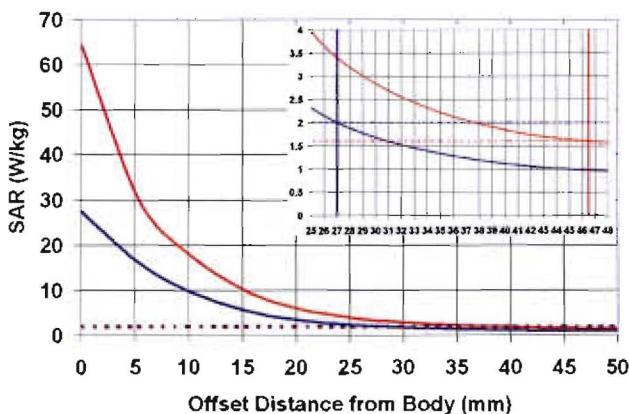

Fig. 23 SAR 1g and 10g against Offset Distance from Body (Box Phantom) for 2450MHz

CONCLUSIONS

In government and industry, various specifications are adopted, some which are more stringent then others. Two specifications widely adopted in the US and Europe is the IEEE 1528 and the IEC 62209. In this paper, modeling and simulation was used to predict safe placement locations of the MegaWave BWA on the Soldier at different frequencies. All models were validated and there was good agreement against published results. The MegaWave BWA model was also validated. All models assumed there were no absorbing materials within the box phantom model and the MegaWave BWA.

If the 1g SAR is adapted, within the frequency band of the MegaWave BWA, the safe standoff distance must be at least 46mm. If the 10g SAR is adopted, with the frequency band of the MegaWave BWA, the safe standoff distance must be at least 37mm

REFERENCES

[1] K.S. Kunz, R.J. Luebbers, "The Finite Difference Time Domain for Electromagnetics", CRC Press, 1993, pp 10-50, 91

[2] IEEE Standards Coordinating Committee 24, "1528 IEEE Recommended Practices for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head for Wireless Communications Devices: Measurements Techniques," pp. 1-90, 2003